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1. Your reference — P.77228 TAC/JCC

2. Patent application number *(The Patent Office will fill in this part)* — **9915181.3** — 29 JUN 1999

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

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Patents ADP number *(if you know it)* 6201875002a

If the applicant is a corporate body, give the country/state of its incorporation: UNITED KINGDOM

4. Title of the invention

AMPEROMETRIC SENSOR

5. Name of your agent *(if you have one)*

J A KEMP & CO

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

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LONDON WC1R 5LX

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer "Yes" if:*
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Yes

AMPEROMETRIC SENSOR

In general terms the present invention relates to the determination of the concentration of an analyte in a sample. More specifically, the invention relates to an amperometric sensor, to its use, to cartridges for the sensor and to redox mediator compounds for use in the sensor.

A number of electrochemical sensors (or biosensors) have been proposed previously. For example, US 5, 288, 636 describes a sensor useful for determining glucose concentration in a sample and relies on the reaction between the enzyme glucose oxidase and glucose with the mediator potassium ferricyanide to produce a ferrocyanide which is then electro-oxidised to produce a measurable current that is representative of the concentration of glucose present.

The reactions involved can be summarised as follows:

1. GOD_{OX} + glucose $\rightarrow$ gluconic acid + GOD_{RED}

2. $GOD_{RED} + M_{OX} \rightarrow GOD_{OX} + M_{RED}$

3. $M_{RED} \rightarrow M_{OX} + e^-$ [Signal]

GOD_{OX} - oxidised form of glucose oxidase
GOD_{RED} - reduced form of glucose oxidase
M_{OX} - oxidised form of mediator (ferricyanide)
M_{RED} - reduced form of mediator (ferrocyanide)

In step 1 the enzyme oxidizes the glucose and is itself reduced. In step 2 the reduced form of the enzyme reacts with the oxidised form of the mediator to produce the reduced form of the mediator. In step 3 the oxidised form of the mediator is regenerated by electro-oxidation. A measurable current/signal is generated. Thus, this type of sensor depends on reaction between the mediator and enzyme.

US 4,711,245 also describes a sensor for determining glucose concentration. The sensor relies on a reaction involving the enzyme glucose oxidase, glucose and the oxidised form of a substituted ferrocene. The ferrocene is reduced and then re-oxidised to produce an easily measurable current.

There are several disadvantages associated with known sensors. Firstly, the mediators used can be unstable and tend to undergo autoxidation. Secondly, in known sensors a potential is applied between electrodes in order to oxidise the reduced form of the mediator. At potentials which are sufficient to achieve this interferants present in the system, for example ascorbates, urate and paracetemol, tend to be oxidised. Both of these effects lead to inaccurate measurement of analyte concentration. In the latter case, the analyte concentration is typically overestimated due to a non-specific oxidation current. With respect to this particular problem, it would be advantageous to use the sensor at assay potentials more negative than +100 mV (Ag/Ag Cl) to avoid measuring signal due to common interferants.

The present invention solves these problems by use of a sensor which relies on the reaction between a mediator compound and hydrogen peroxide. The hydrogen peroxide may be the analyte it is desired to assay or it may be the product of an enzyme-analyte reaction. An important feature of the sensor is that in the reduced form the mediator can be detected electrochemically at a potential of about -400 mV (Ag/AgCl). At such a potential oxidation of common interferants is avoided.

Accordingly, the present invention provides an amperometric sensor suitable for determining the concentration of hydrogen peroxide in a sample, said sensor comprising a ferricyanide compound which, in reduced form, functions as a mediator selective to hydrogen peroxide.

The sensors of the invention may, of course, be used to determine the concentration of H_2O_2 in a sample. However, as is evident from the reaction scheme above, H_2O_2 may be generated as a product of an analyte-enzyme reaction, such as between glucose-glucose oxidase. The sensors can therefore be used to determine the concentration of such analytes. In this embodiment the sensor further comprises an enzyme which is capable of reacting with the analyte in a sample to produce hydrogen peroxide. Typically, the enzyme will be an oxidase type enzyme. For

example, in a sensor for determining the concentration of glucose in a sample, the enzyme may be glucose oxidase. The reaction between the enzyme and analyte yields H_2O_2 in the presence of oxygen, and the concentration of the hydrogen peroxide can be determined using the sensor and correlated to a corresponding glucose concentration. Other analytes which may be determined using the sensor of the present invention include chloresterol, pyruvate, bilirubin, alcohol and lactate; USP 5,288,636 gives details of the relevant enzymes and mediators.

Further analytes may be measured if suitable additional enzymes and/or mediators are included in the sensor. Examples of this include triglycerides and HDL cholesterol of course the sensors should be constructed so that the final product of the enzyme reactions detected by the ferricyanide mediator, is hydrogen peroxide.

Herein the term "mediator" means a compound which is capable of undergoing an electrochemical, reversible oxidation-reduction reaction.

The mediator used in the present invention is a ferricyanide compound which in reduced form is selective for hydrogen peroxide, i.e. which is oxidised on reaction with hydrogen peroxide. Examples of suitable compounds include those of general formula $X_3Fe(CN)_6$ in which the groups X are the same or different and each is a non-metallic ion. Preferably the mediator is specific to hydrogen peroxide, i.e. under the conditions of the analysis, the mediator only provides electrons for hydrogen peroxide. In practice it is likely that this will be the case when operating at the preferred potential (see below). However specificity is not essential and the system may be operated satisfactorily provided that the mediator is selective for hydrogen peroxide, i.e. under the conditions of the analysis the mediator tends to provide electrons to hydrogen peroxide in preference to any other electron acceptor available to the mediator.

In this formula X may be a quaternary ammonium ion, for instance of formula $(R_1)(R_2)(R_3)(R_4)N^+$ in which R_1-R_4 are the same or different alkyl groups containing from 1 to 20 carbon atoms, provided that a least one of R_1-R_4 contains at least 4 carbon atoms. Typically, R_1-R_4 are selected from amongst alkyl groups containing from 4 to 20 carbon atoms, preferably from 4 to 16 carbon atoms. Conveniently the quaternary ammonium ion will have four identical alkyl groups in

which case they alkyl groups are preferably selected from those of 5 to 11 carbon atoms. As an alternative the quaternary ammonium ions may conveniently have only one long chain alkyl group and three identical short chain alkyl groups such as methyl groups. In this case the long chain alkyl group is preferably selected from those of 6 to 20 carbon atoms.

The longer alkyl groups render the quaternary ammonium ions relatively insoluble which is an advantage in the present invention. It is preferred that the quaternary ammonium ions used have a solubility of not more than 100 $mg.L^{-1}$ in water at room temperature (20 C), more preferably not more than 10 $mg.L^{-1}$ and most preferably not more than 1 $mg.L^{-1}$. As specific examples of useful compounds there may be mentioned tetrahexyl-, hexyltrimethyl-, tetrakisdecyl-, tetradecyltrimethyl- and hexadecyltrimethylammonium ferricyanides.

In an embodiment of the invention, the group X may be a phosphonium ion, for example of formula (R_5) (R_6) (R_7) (R_8) P^+ in which R_5-R_8 are the same or different alkyl groups containing from 1 to 20 carbon atoms, provided that at least one group R_5 - R_8 contains at least 4 carbon atoms.

In another embodiment the group X may be a nitrogen-containing heterocyclic cation. The heterocyclic group may be saturated, unsaturated or aromatic. As an example, X as pyridinium may be mentioned.

The alkyl groups mentioned above may be straight-or branched-chain. The alkyl and heterocyclic groups may be substituted by one or more substituents provided that these do not have a detrimental effect on the activity of the mediator compounds.

Some of the compounds useful as mediators are known and are commercially available. Alternatively, they may be made by the application or adaptation of known techniques. Certain of the mediator compounds are new however and these form another aspect of the present invention. Thus, the invention also provides novel ferricyanide compounds of the above formula in which at least one X is a quaternary ammonium ion having at least one C_6-C_{20} alkyl group other than tridodecylmethyl-, methyltrioctyl-, dihexadecyldimethyl-, didodecyldimethyl-, hexadecyltrimethyl and tetraoctylammonium ions.

These ferricyanide compounds may be prepared by methods described in Svitel, J *et al.*, Electroanalysis, 1998, 10, No. 9, pp 591-596, and modifications thereof, using appropriate quaternary ammonium halides and ferricyanide salts. In general, a quaternary ammonium halide such as the chloride or preferably the bromide, is reacted with a ferricyanide salt, preferably an alkali metal salt such as sodium or, more preferably, potassium ferricyanide. The reaction may be conducted under suitable conditions of temperature and pressure, such as at room temperature or elevated temperature up to the boiling point of the reaction mixture, and at atmospheric pressure, and for sufficient duration such as from a few minutes to a few hours, preferably at 80°C for 2 hours, in the presence of a suitable solvent such as water.

The mediator compounds disclosed herein are useful in a variety of amperometric sensor devices and electrode configurations. The sensors may be based on a 2 or 3 electrode system and may be of the disposable (single use) or re-usable/semi-disposable type.

In its simplest form the sensor comprises two electrodes (working and counter) which in use are contacted with the sample being analysed. One electrode, the working electrode, is coated with the mediator compound. The mediator is sparingly soluble or insoluble in aqueous solution and may be applied to the electrode by deposition from a solution of the mediator in a readily evaporable organic liquid. When the sensor is being used to determine the concentration of an analyte such as glucose the mediator is coated with a suitable enzyme. The enzyme can be immobilised on the surface of the mediator by conventional techniques such as by use of a self-sustaining gel layer and/or by use of a retention layer which is permeable to the analyte. US 4,711,245 describes in greater detail ways in which the mediator and, when used, enzyme may be fixed on the working electrode.

The electrode substrate is chosen from conventional materials such as carbon pellets, carbon inks, metallized carbon and metals (such as platinum or palladium), carbon rods, pencil leads and carbon rods loaded with metal powder.

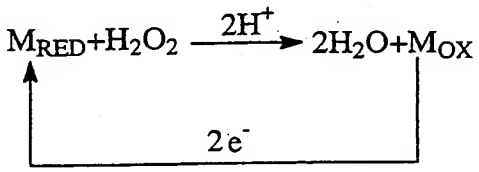
Conventional electrode configurations which may be used include those disclosed in US 4,711,245, US 5,200,051 and US 5,288,636, incorporated herein by

reference.

The basic chemical and electrochemical transformations associated with the present invention are shown below with reference to the glucose/glucose oxidase system. Prior to introduction of the sample to be analysed a potential of about -400mV (Ag/AgCl) is applied between the sensor electrodes. This potential is sufficient to cause reduction of the mediator at the working electrode, i.e. conversion of the ferricyanide to the corresponding ferrocyanide. When the electrodes are contacted with the sample to be analysed the enzyme at the working electrode acts on the glucose resulting in the production of hydrogen peroxide. The reaction proceeds as shown in reaction scheme 4 below.

$$GOD_{RED} + O_2 \rightarrow GOD_{OX} + H_2O_2$$

The hydrogen peroxide produced oxidises the reduced form of the mediator as follows:



Instantaneously, under the applied potential, the oxidised form of the mediator at the working electrode is converted to the reduced form and a diffusion limited current generated. This current can be measured and correlated to the concentration of analyte in the sample.

At the electrode potential involved (-400 mV) there is no oxidation of interferants and the result obtained is an accurate reflection of the hydrogen peroxide concentration in the sample. The hydrogen peroxide concentration may be correlated

to analyte concentration.

A diffusion limiting layer may be applied to the working electrode to extend the sensor to measurement of higher analyte concentrations. Examples of materials for use as the diffusion-limiting include Nafion and cellulose acetate.

It is envisaged that the sensors of the invention will find most practical utility in the measurement of glucose in blood samples, although they may also be used for other medical and non-medial applications, for example in the food industry.

The following Examples illustrate the invention but are not intended to limit the scope of protection in any way.

EXAMPLES

Example 1 Synthesis of mediator

Tetrahexylammonium ferricyanide was prepared by adding an aqueous solution of potassium ferricyanide (Aldrich, Dorset, U.K.) (0.5mmole 1.65g) into a solution of tetrahexylammonium bromide (Aldrich, Dorset, U.K.) (1.5mmole, 0.65g) in 20ml of distilled water and heating the mixture to 80°C for 2 hr with vigorous stirring. A yellow coloured oil separated from the acqueous phase and was extracted with diethylether (3x10ml). The ethereal extract was washed with distilled water (3x10ml) and then dried over magnesium sulphate. Evaporating the solvent gave 1.1g of yellow oil which solidified on standing.

Example 2 Electrode construction

A silver loaded carbon pellet (Electrocarbon, Norfolk, U.K.) with a diameter of 2mm and a length of 4mm was fitted with a 1.8mm internal diameter PVC rubber tubing section (4mm in length) so that a recess of about 1mm was left at one end. The other end of the pellet was fixed to a 5cm long copper wire with silver expoxy glue as contact. The whole assembly was then fitted into another 4.5cm long PVC tubing that fitted the electrode assembly tightly. The opening at the end of the tubing with exposed contact wire was then sealed with epoxy glue. The finished electrode assembly has an electrode area of 3.1mm^2.

Example 3 Hydrogen peroxide sensor

1uL of a 5.5% ethanolic solution of tetrahexylammonium ferricyanide (Example 1) was deposited onto the recess of the electrode prepared in Example 2 and allowed to dry for 3 minute. A 1uL aliquot of Nafion™ solution (5% solution from Aldrich, Dorset, U.K.) in distilled water (9:1 mixture, final concentration 0.5%) was deposited on top of the ferricyanide layer to form a diffusion control membrane. The sensor was air-dried for at least 4 hr before use.

Example 4 Glucose sensor

This biosensor was formed in a manner similar to that for the hydrogen peroxide sensor of Example 3 except that an enzyme layer was added in between the ferricyanide layer and the diffusion control layer. The enzyme layer used was made from two solutions:

Solution A: propanoic solution containing 2.2% tetrahexylammonium ferricyanide and 1.25% Nafion™.

Solution B: glucose oxidase solution (5mg/ml ~200U/mg) (Fluka, Dorset, U.K.).

A 1:1 mixture of solution A and solution B was prepared immediately before use and a total of 10ul were deposited onto the tetrahexylammonium ferricyanide modified electrode in 2uL aliquots. The sensor was dried in a gentle stream of air (~30min,) before a 1uL aliquot of 0.5% Nafion™ solution in water was deposited over the enzyme layer. The sensor was air dried as before and kept dry at 4°C overnight before use.

Example 5 Use of Hydrogen peroxide sensor

Cyclic voltammetry was used to show the activity of this sensor to hydrogen peroxide. A three electrode system was used with the sensor of Example 3 as the working electrode, a platinum electrode as the counter electrode and a silver-silver chloride electrode as the reference electrode. An AutoLab (Eco Chemie B.V.) electrochemical system was used for the measurements. Cyclic voltammetry at a scan rate of 50mV/s and a scan range of 1.0V to 1.5V vs Ag-AgCl shows the increase

in cathodic current when aliquots of 131mM hydrogen peroxide (200uL and 700uL) in phosphate saline buffer solution were added into 4ml of the same buffer solution at pH 7.4. The same cell set up was used for calibration of the sensor by amperometry; the current measured at the hydrogen peroxide sensor at an applied potential of -400mV vs Ag-AgCl during an experiment where aliquots of 131mM hydrogen peroxide in phosphate saline buffer were added to 4ml of the same buffer was plotted A calibration plot resulting from the amperometry data shows a linear range from 0-~20mM hydrogen peroxide.

Example 6 Use of Glucose sensor

Similar experiments to those of Example 5 were carried out using the glucose sensor of Example 4 in the same cell set up, except that the counter electrode used was a gold electrode. For all cases the buffer used for making up glucose solution and the blank (background) was phosphate saline buffer at pH7.4. The scan rate for cyclic voltammetry measurement was 100mV/s and the scan range used was 0.15V to -0.55V. The cyclic voltammagram obtained for different glucose concentrations shows cathodic currents at around -400 mV that indicate that the biosensor responded to hydrogen peroxide, which was produced by the action of the glucose oxidase on the glucose added and that the increase in cathodic current was concentration dependent. The current measured at the glucose sensor at an applied potential of -400mV vs Ag-AgCl during an experiment where aliquots of 50mM glucose in phosphate saline buffer were added to 4ml of the same buffer shows a linear range from 0 - ~30 mM glucose.

CLAIMS

1. An amperometric sensor suitable for determining the concentration of hydrogen peroxide in a sample, said sensor comprising a ferricyanide compound which, in reduced form, functions as a mediator selective for hydrogen peroxide.

2. A sensor according to claim 1, further comprising an enzyme which is capable of reacting with an analyte in the sample to produce hydrogen peroxide.

3. A sensor according to claim 2, wherein the analyte is glucose and the enzyme is glucose oxidase.

4. A sensor according to any one of claims 1 to 3, wherein the ferricyanide compound is of general formula:

$$X_3\ Fe\ (CN)_6$$

in which the groups X are the same or different and each is a non-metallic ion.

5. A sensor according to claim 4, in which each X is a quaternary ammonium ion of formula $(R_1)\ (R_2)\ (R_3)\ (R_4)\ N^+$ in which R_1-R_4 are the same or different alkyl groups containing from 1 to 20 carbon atoms, provided that a least one of R_1-R_4 contains at least 4 carbon atoms.

6. A sensor according to claim 5, wherein the ferricyanide compound is tetrahexylammonium ferricyanide, tetrakisdecylammonium ferricyanide, tetradecyltrimethylammonium ferricyanide, hexadecyltrimethylammonium ferricyanide or trimethylhexylammonium ferricyanide.

7. A sensor according to claim 4, wherein each X is a phosphonium ion of formula $(R_5)\ (R_6)\ (R_7)\ (R_8)\ P^+$ in which R_5-R_8 are the same or different alkyl groups containing from 1 to 20 carbon atoms, provided that at least one group R_5-R_8 contains at least 4 carbon atoms.

8. A sensor according to claim 4, wherein each X is a nitrogen-containing heterocyclic cation.

9. A sensor according to claim 8, wherein each X is a pyridinium ion.

10. A cartridge for an amperometric sensor suitable for measuring hydrogen peroxide in a sample, which cartridge comprises a ferricyanide compound

as defined in any one of claims 1 and 4 to 9.

11. A cartridge according to claim 10, further comprising an enzyme as defined in claim 2 or 3.

12. Use of an amperometric sensor as claimed in any one of claims 1 and 3 to 9 for determining the concentration of hydrogen peroxide in a sample.

13. Use of an amperometric sensor as claimed in claim 2 for determining the concentration of an analyte in a sample, wherein the enzyme of the sensor reacts with the analyte to produce hydrogen peroxide.

14. A ferricyanide compound of formula:

$$X_3 Fe (CN)_6$$

in which the groups X are the same or different and each is a quaternary ammonium ion, at least one of the quaternary ammonium ions having (a) four identical alkyl groups of 5 to 11 carbon atoms other than heptyl or (b) three methyl groups and an alkyl group of 6 to 20 carbon atoms other than hexadecyl.

15. A compound according to claim 14 wherein each X is a quaternary ammonium ion selected from hexyltrimethylammonium, heptyltrimethylammonium, octyltrimethylammonium, nonyltrimethylammonium, decyltrimethylammonium, tetradecyltrimethylammonium, hexadecyltrimethylammonium, tetrahexylammonium and tetrakisdecylammonium.

16. A compound according to claim 14 or claim 15 wherein the groups X are all the same.

17. A process for preparing a ferricyanide compound as defined in claim 14, which process comprises reacting a quaternary ammonium halide having (a) four identical alkyl groups of 5 to 11 carbon atoms other than heptyl or (b) three methyl groups and an alkyl group of 6 to 20 carbon atoms other than hexadecyl with an alkali metal ferricyanide salt.